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Supplementary information

Fire enhances forest degradation within forest edge zones in Africa

In the format provided by the authors and unedited

Supplementary Materials

Supplementary Methods

Different types of forests and edges

As shown in Extended Data Fig. 8, forest and edge pixels were classified into different types in our study.

When calculating edge effects across Africa, forest pixels (30 m)[1] were firstly separated into moist (**M**) and dry (**D**) forests using the MODIS land cover map (500 m) (MCD12Q1, version 6)[2] to avoid the fitting biases induced by the biomass gradient between these two forest types. Moist forests comprise Evergreen Broadleaf Forests, Deciduous Broadleaf Forests and Mixed Forests, while dry forests comprise Savannas and Woody Savannas. Next, to quantify the fire impacts on edge effects, we defined forest pixels with fire-related edges as forests influenced by fire. Forests having suffered fire, but without fire edges, were not included in our study (mainly natural fires, e.g. ignited by lighting). We overlaid the forest edges on the FireCCI burned area data set (250 m)[3], and the edge pixels that had experienced at least one fire event during 2004-2009 were set as fire edges, while the other edge pixels were set as non-fire edges. Forest pixels in the same grid cell are separated according to their nearest edge types (fire: **MF/DF**, non-fire: **MN/DN**), and then the edge effect curves are fitted separately. Values of β were averaged over fire and non-fire edges separately in the same 0.25° grid cell, and $\Delta\beta$ (fire minus non-fire β) was used as indicator of the indirect fire impact on edge effects.

Forest pixels with fire edges were further separated, according to whether fire intruded into forests, to calculate fire distance (fire intrusion: **MF_F/DF_F**, no fire intrusion: **MF_N/DF_N**). Fire distance was set as the distance to edge (d) for forest pixels with fire intrusion (**MF_F/DF_F**), and set to 0 for those pixels without fire intrusion (**MF_N/DF_N**). Then the median of the fire distances of forest pixels with fire edges was used for each 0.25° grid cell (**MF/DF**). Therefore, the fire distance also potentially reflects the area of forests with fire intrusion.

Supplementary Discussion 1: Comparison with previous studies

Methods of previous edge effect studies

Forest edge effects have been studied using field studies, fragmentation experiments, remote sensing data and models. Field studies generally focus on specific variables affected by edge effects such as temperature and carbon storage[4,5], but are not able to isolate edge effects from the impacts of long-term climate change and surrounding environment change[6]. Long-term fragmentation paired-experiments can quantify the temporal dynamics of edge effects[6,7]. These experiments are performed over forest fragments of different shapes and sizes which are maintained by artificial disturbances, compared to control and replication areas to exclude other factors (e.g. climate change, surrounding environment). The development of remote sensing products has made it possible to estimate large-scale AGB heterogeneities[8]. Briant et al.[9] pioneered the use of such products to calculate the carbon deficit due to forest edges in eastern Amazonia. Chaplin-Kramer et al.[10] extended the approach to the pan-tropics, using the 500 m resolution AGB fields derived from optical measurements with the MODIS sensor. Combining remote sensing data with a process-based, forest-stand dynamics model resolving edge-induced disturbances on species selection, tree growth and mortality, Puetz et al.[11,12] estimated an additional carbon loss due to edge effects in the Brazilian Atlantic and Amazon forests.

Comparisons of scales in our study with those in previous studies

The scales of edge effects in our study ($0.11^{+0.06}_{-0.04}$ km and $0.15^{+0.09}_{-0.05}$ km for moist forests and dry forests) across Africa are similar to previous field observations. Broadbent et al.[13] showed that most of the edge impacts (including forest structure, tree mortality, forest microclimate and biodiversity) extend within 300 m. In the Amazon fragmentation experiments, increased tree mortality and recruitment were found within 300 m of the forest edges[14]. Based on data from field plots within intact forests, the AGB deficit was found to extend up to 448 m from forest edges in Borneo[4].

However, the scales calculated using coarser resolution remote sensing data are larger than our results and field observations. By using 500 m resolution MODIS images (MOD09A1), Briant et al.[9] showed that desiccation conditions could extend up to 2.7 km from forest edges. Chaplin-Kramer et al.[10] used MODIS data (500 m), along with the Baccini et al. biomass map (500 m)[8], and found that edge effects penetrate 1.5, 0.8 and 1.4 km in moist, dry and all forests. We aggregated both the forest map (30 m) and the biomass map (30 m) to 500 m and recalculated the edge-scales. The recalculated weighted mean scales for both moist and dry forests increase to 1.2 km (Fig. S7, Table S3). These results confirm an overestimation of forest edge scales in previous studies caused by coarser data resolution.

Comparisons of carbon deficit due to edge effects in our study with those in previous studies

With an assumption of edge effects parameters similar to our results (edge penetration distance *d*=100 m and carbon deficit within the edge zones of 50 %), Brinck et al.[15] estimated a carbon deficit of 3.56 Pg C due to edge effects in Africa, based on the biomass map (1000 m) of Saatchi et al.[16] and the Hansen forest map (30 m)[1] , which is close to our estimate of 4.06 Pg C.

We found a carbon deficit of 31% within the forest edge zones. This estimate is higher than the average carbon deficit of all plots (8.8% within 100 m of the forest edges) in Laurance et al.[17], but similar to their highest carbon deficit (36%) in some plots. Our calculation of carbon deficit in Africa includes the long-term total deficit, while the field observations lasted 10-17 years in new forest fragments in Amazon. The overall higher biomass density at the observation sites in Amazon, compared to the whole forest region of Africa, may also contribute to the difference. Another possible reason is that our study included more forest edges from small fragments than Laurance et al.[17]. Puetz et al.[11] estimated edge effects using an individual-based, stand-dynamics model and found that small forest fragments (< 25 ha) suffer 60 % biomass deficit at the community level, which is much larger than our result (31%).

Supplementary Discussion 2: Disturbance impacts on edge effects

Agriculture, construction, fire and logging

Different disturbance types at forest edges may impact the edge effects, but the high-resolution forest disturbance data for Africa is scarce. We thus used the samples of different types of disturbances based on visual interpretation of Landsat images and other available very high resolution data for the Congo Basin (Fig. S1e) made by Tyukavina et al. (2018)[18]. We first counted the sample number of different disturbance types in each 0.25° grid cell and assumed the disturbance type with the maximum number to be the main disturbance type in each grid cell. The grid cells in this region were thus classified as disturbed by agriculture, construction, fire and logging, as well as non-disturbed (Fig. S1e). The frequency distributions of edge effects in grid cells with various disturbance types are shown in Fig. S1. Moist forests edges with fire disturbance have larger scale and magnitude than those without recent disturbances, which is consistent to our results. In dry forests, fires increase the magnitude but decrease the scale of edges. The scale and magnitude of edge effects are lower in regions with disturbances of agriculture, construction and logging than in the non-disturbed regions. One possible reason is that these disturbances occurred during 2000-2010, and the states of edge forest may not reach equilibrium. In this case, it may cause underestimation of carbon deficit of edge effects. Due to lack of reliable high-resolution disturbance data for the whole studied region, we only separate the impacts of different disturbance types on the edge effects in the Congo Basin rather than the whole Africa.

Fragmentation

To analyze the impact of fragmentation on edge effects, we calculated the area of each forest patch and defined forest patches with an area <100 km^2 as isolated forest fragments in each 0.25° grid cell[19]. We further classified the grid cells into two categories based on whether the fraction of isolated forest area is > 1% of the total forest area in each grid cell. Frequency distributions of edge effects in these two categories are shown in Fig. S2. Only the magnitude of moist forests shows some difference while others are similar, probably due to the low fraction of isolated fragments in the total forest area in each grid cell. Therefore, the impact of fragmentation on edge effects would be small at the grid cell level.

Newly created edges

Forests with newly created edges from recent deforestation may not reach equilibrium, which would cause underestimation of carbon deficit in these new edge forests. We thus separated the edges into old (created before 2000) and new (created during 2000-2010) edges using the forest loss data from Hansen et al. (2013)[1]. The new edges account for 66% and 19% of all edges for moist and dry forests. Similar to the analyses of fire impacts on edge effects, we estimated scale and magnitude for forests with old and new edges separately in the same grid cell and compared their differences. As shown in Table S1, the scales with old edges are larger than those with new edges in most grid cells (71% and 59% grid cells for moist and dry forests). In these grid cells, the difference in scales is $0.09_{-0.05}^{+0.08}$ and $0.06_{-0.03}^{+0.06}$ km for most and dry forests. Similarly, the magnitudes with old edges are also larger in 80% and 67% grid cells for moist and dry forests with a difference of 27_{-14}^{+18} % and 19_{-9}^{+15} %. Therefore, forests with old edges have larger edge effects than forests with new edges, indicating that new edge forests have not reached equilibrium. The equilibrated carbon deficit would be larger than our current estimate.

Supplementary Discussion 3: Uncertainty

Uncertainties in the forest cover map and impact of plantations on edge effects

We used the latest version of the forest cover and loss data (v1.7, https://earthenginepartners.appspot.com/science-2013-global-forest/download_v1.7.html). Relative to the old version (v1), the data after 2011 is reprocessed using an improved loss detection method, which may lead to inconsistency before and after 2011. This dataset also lacks a full validation of incorporationg Landsat 8 (launched in 2013) for loss detection. However, these caveats have limited impact on our analyses since we mainly focus on the forest loss before 2010. Tropek et al. (2014)[20] showed that using the forest definition of "all vegetation taller than 5 m in height", the plantations in the tropic were usually recognized as forests in the forest cover maps of Hansen et al. (2013)[1]. In regions with plantations expansion into forests, forest area is thus overestimated and forest loss is underestimated in the data of Hansen et al. (2013)[1]. Plantations have distinct ecological values from forests, such as biodiversity richness and carbon storage. The edge effects may be also different between native forests and plantations. To analyze the impact of plantations on edge effects, we first identified whether plantations exist in each grid cell using the Planted Forests data from Global Forest Watch (https://data.globalforestwatch.org/datasets/planted-forests). We found that plantations exist in 16% and 19% of the 0.25° grid cells with edge effects (Fig. S5). In these grid cells, we further fitted the edge effect curve separately for plantation pixels and native forest pixels and compared their differences in the edge effects. The scales and magnitudes of plantation edge effects are smaller than native forests for both moist and dry forests (Fig. S6), probably because the managements in the plantations alleviate the biomass decrease in the plantation edge zone. The interaction between plantations and native forests, however, was not assessed in our analyses. A recent study showed that edge effects from oil palm plantations can extend over 300 m into native forests[21].

Results from other fitting models

In addition to the original von Bertalanffy asymptotic curve (Chaplin-Kramer et al., 2015), we tried another two fitting curves (Hyperbola and Sigmoid) to test the impacts of fitting models to the results of edge effects. To test the impacts of fitting models to the results of edge effects, we tried other two equations as fitting models: Hyperbola and Sigmoid. We selected

Hyperbola and Sigmoid because they can both fit the biomass at the edge and at the interior forests, thus scale and magnitude can be estimated. As shown in Table. S2, the numbers of grids with edge effects using Hyperbola and Sigmoid models are less than that using the original model (65% and 75% for moist and dry forests using Hyperbola, and 67% and 75% for moist and dry forests using Sigmoid). The scales and magnitudes of edge effects from the Sigmoid model are very close to the original results, while the scales and magnitudes from the Hyperbola model are slightly higher than the original results fitted using the original model. All the scales are still within the range of field observations (about 100-300 m). We also tested a linear regression model and found a significant correlation ($p<0.01$) between AGB and distance to edge in 93% and 96% of the grid cells for moist and dry forests, verifying the existence of AGB gradient from edge to interior forests.

Impacts of natural variability of AGB on the edge effect estimations

The edge area is very sensitive to the threshold used to define the interior forest biomass, and hence the scale from the edge effect curve. If we change the threshold of 90% to 65% (assuming a 35% CV of interior forest AGB representing natural variability), the edge area will decrease by 87% and 60% for moist and dry forests. However, we should note that the scale is a statistical value from the curve fitting in each 0.25° grid cell, which mainly reflects the relationship between AGB and distance to edge. The forest edge area was further calculated from forest pixels with the distance to edge smaller than the scale rather than based on the AGB. We argue that natural variability occurs randomly in the space, and there would be no relationship between AGB and distance to edge. Therefore, the natural variability of interior forest could affect the edge effect curve fitting, reflected by the relatively lower R^2 (Fig. S4), but it is marginally relevant to the definition of the scale and the edge area.

Supplementary Table

Table S1. Difference of edge effects between old and new edges. Old edges are defined as edges created before 2000, while new edges are edges created during 2000-2010. The new edges account for 66% and 19% of all edges for moist and dry forests.

	Scale		**Magnitude**	
	Fraction of old > new (%)	old – new (km)	Fraction of old > new (%)	old – new (%)
Moist forests	71	$0.09^{+0.08}_{-0.05}$	80	27^{+18}_{-14}
Dry forests	59	$0.06^{+0.06}_{-0.03}$	67	19^{+15}_{-9}

Table S2. Scale, magnitude and fraction of grid cells with detected edge effects using different fitting models.

Method	**Moist forests**			**Dry forests**		
	Scale (km)	Magnitude (%)	Grid cells with fitted edge effects (%)	Scale (km)	Magnitude (%)	Grid cells with fitted edge effects (%)
Original	$0.11^{+0.06}_{-0.04}$	36^{+10}_{-9}	73	$0.15^{+0.09}_{-0.05}$	54^{+12}_{-11}	82
Hyperbola	$0.12^{+0.13}_{-0.05}$	47^{+14}_{-11}	65	$0.35^{+0.29}_{-0.17}$	64^{+12}_{-12}	75
Sigmoid	$0.11^{+0.06}_{-0.03}$	33^{+10}_{-9}	67	$0.15^{+0.09}_{-0.06}$	51^{+11}_{-11}	75
Linear			93 ($p<0.01$)			96 ($p<0.01$)

Table S3. Weighted mean edge effects derived from different data sets. Note that *magnitude* is defined as the relative difference of AGB between the edge and the interior of forests. The edge (the outer forest pixel in a forest patch) is determined by the pixel resolution, so the magnitude is calculated using a distance of 15 m (half of the pixel size) away from the edges for the 30 m data and 232 m for the 500 m data. The difference in magnitude between our study and Chaplin-Kramer et al. is mainly because different regions were analyzed. Chaplin-Kramer et al. estimated edge effects mainly in the dense forests of the Congo basin in Africa, whereas our study detected little edge effect in these areas (Fig. 1).

	Chaplin-Kramer et al.		**This study (500m)**		**This study (30m)**	
	moist	dry	moist	dry	moist	dry
Scale (km)	1.5	0.8	1.2	1.2	0.15	0.21
Magnitude (15 m, %)			64	77	37	55
Magnitude (232 m, %)	29	18	46	54	5	8

Supplementary Figure

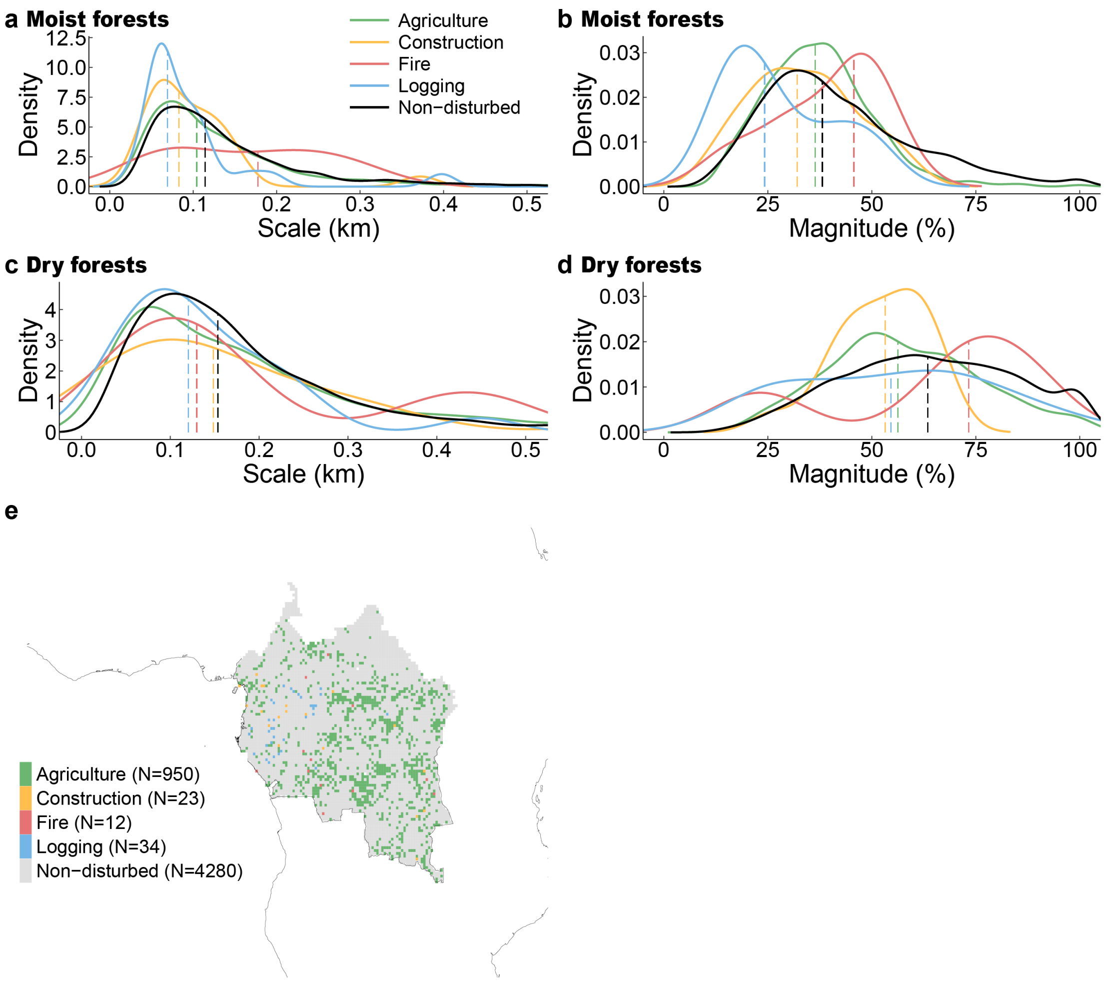

Fig. S1. Frequency distributions of scales (a, c) and magnitudes (b, d) of edge effects in grids with different disturbance types in the Congo region (e). Samples of different disturbances from 2000-2010 in the Congo region are from Tyukavina et al. (2018)[18]. We counted the sample number of different disturbances in each grid and assumed the disturbance type with the maximum number to be the main disturbance type in each grid. Therefore, the grids in the Congo region are classified to be impacted by agriculture, construction, fire, logging and not disturbed. The dashed lines indicate medians. Number of 0.25° grid cells (N) with each disturbance type is shown in the legend (e).

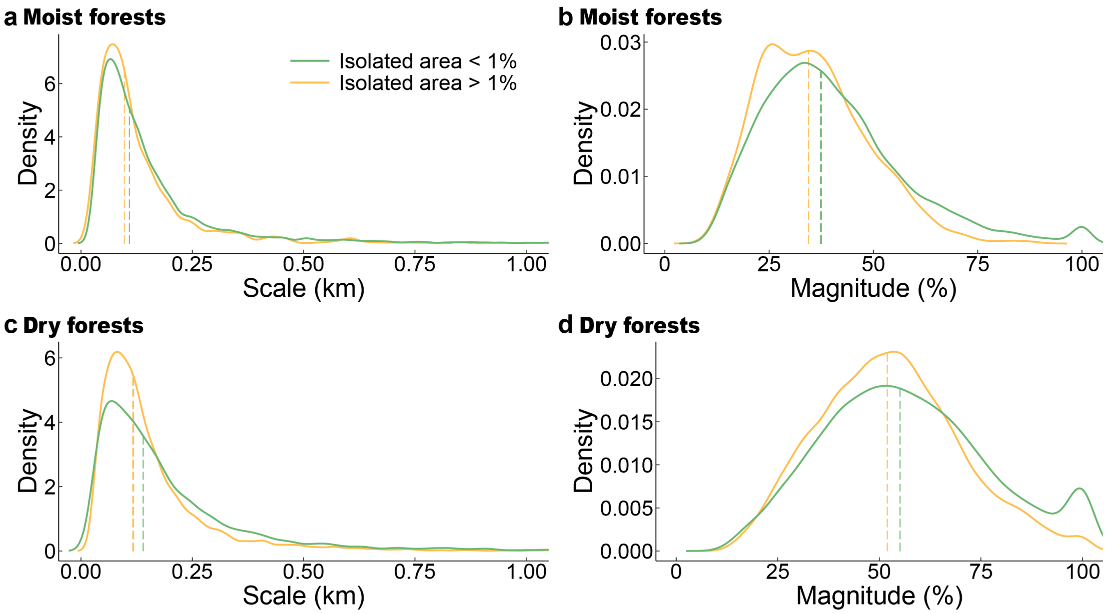

Fig. S2. Frequency distributions of scales (a, c) and magnitudes (b, d) of edge effects in grids with different levels of isolated fragments area in Africa. Isolated fragments are defined as forest fragments with areas < 100 km^2. Grid cells in the Africa are classified according to whether the isolated fragments area > 1%. The dashed lines indicate medians. Numbers of 0.25° grid cells with isolated fragments area >1% are 929 and 6,830 for moist and dry forests, and numbers of grid cells with isolated fragments area <1% are 8,500 and 5,819 for moist and dry forests.

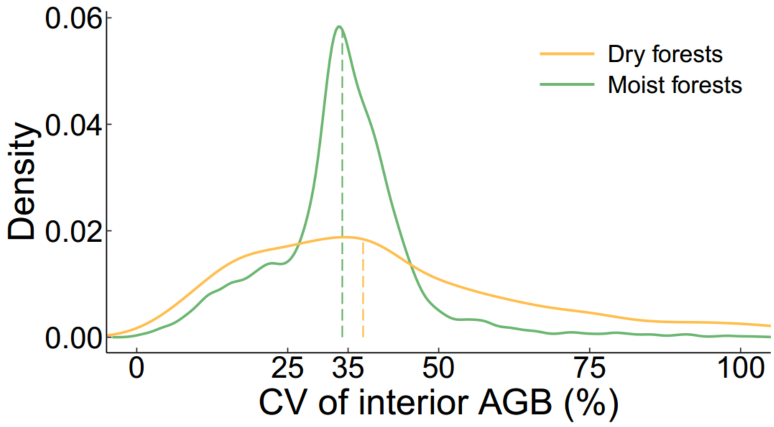

Fig. S3. Frequency distributions of scales (a, c) and magnitudes (b, d) of edge effects in grids with different levels of isolated fragments area in Africa. Isolated fragments are defined as forest fragments with areas < 100 km^2. Grid cells in the Africa are classified according to whether the isolated fragments area > 1%. The dashed lines indicate medians. Numbers of 0.25° grid cells with isolated fragments area >1% are 929 and 6,830 for moist and dry forests, and numbers of grid cells with isolated fragments area <1% are 8,500 and 5,819 for moist and dry forests.

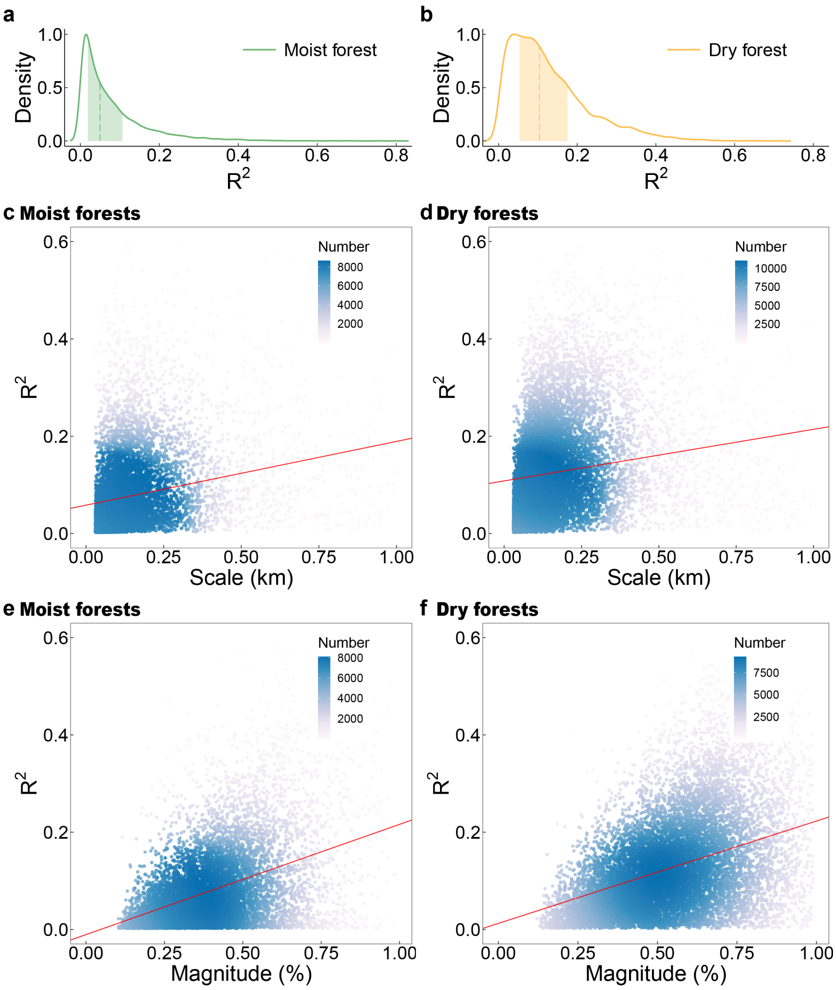

Fig. S4. Frequency distributions of R^2 (a-b) and relationships between R^2 and scale (c-d) and magnitude (e-f) in Africa. (a, c, e) are for moist forests, and **(b, d, f)** are for dry forests. Shading in (**a**) and (**b**) indicates the interquartile ranges, and dashed lines indicate medians. The color scale in (**c**)-(**f**) indicates numbers of data points. R^2 is positively correlated with both scale and magnitude ($p < 0.01$).

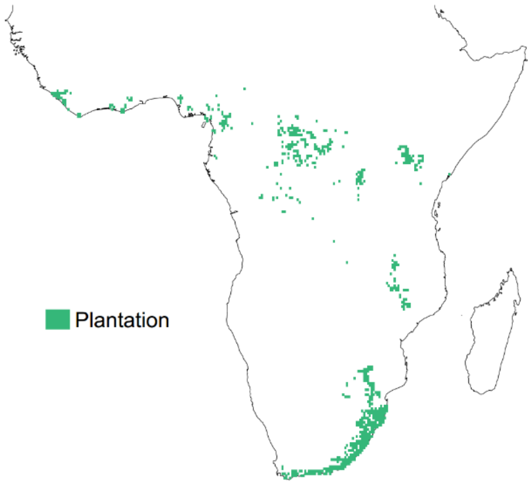

Fig. S5. Spatial distributions of 0.25° grid cells with plantations in Africa

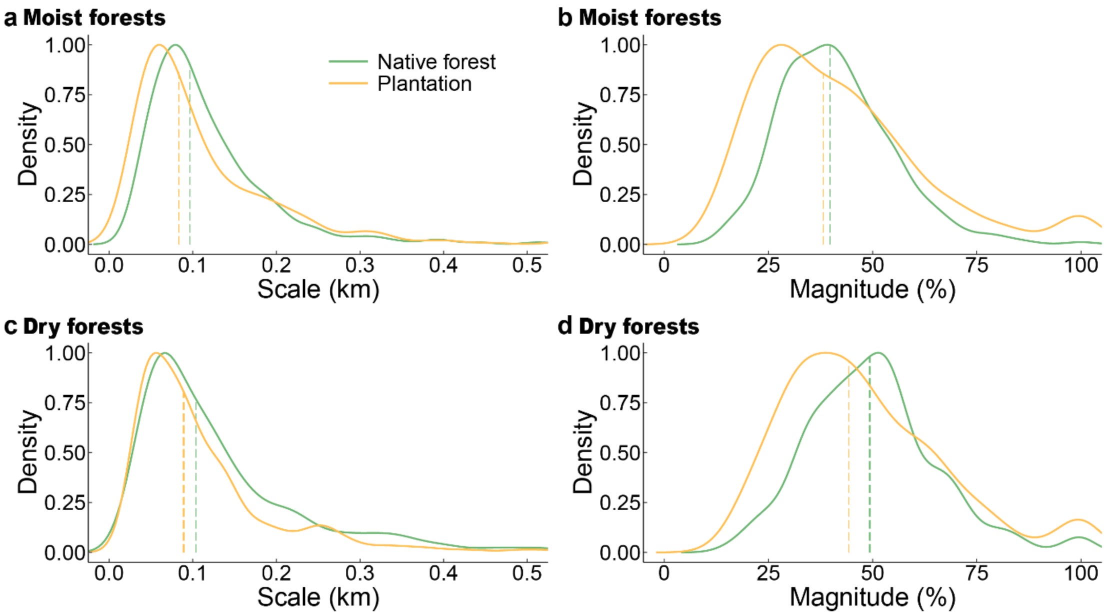

Fig. S6. Frequency distributions of scales (a, c) and magnitudes (b, d) of edge effects in grid cells with plantations in Africa. Forest pixels in the same grid cell were separated into native forests and plantations, and then edge effect curves were fitted separately. The dashed lines indicate medians.

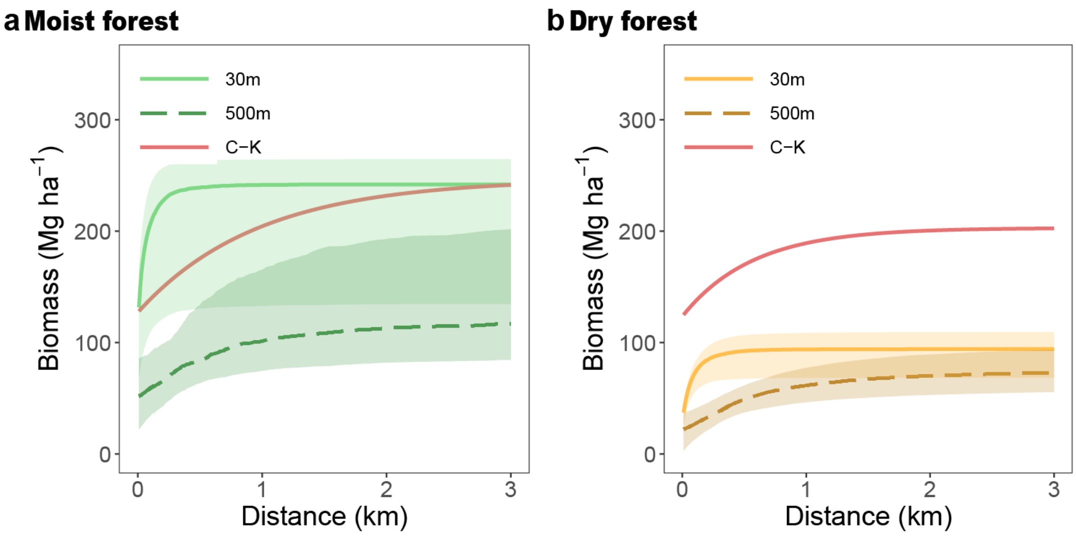

Fig. S7. Comparison of forest edge effects with a previous study. Weighted median curves of edge effect are derived from Chaplin-Kramer et al. (C-K, 2015, 500m MODIS forest + 500m biomass from Baccini et al.), and this study (30m Hansen forest + 30m GlobBiomass and aggregrated 500m Hansen forest + 500m GlobBiomass). Shading indicates weighted inter quartile ranges.

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